CAVITATION INCEPTION

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INTRODUCTION: We are sure that the delegates to the present conference do not need to be reminded that cavitation inception in the pervasive role it occupies in Naval Architectural hydrodynamics remains as a basic problem bedevilling the worker in the laboratory and field alike. One of the more perplexing aspects of this phenomenon has been its lack of repeatability between experiments carried out on similar test bodies in different test facilities or even on different types of bodies in the same test facility. In addition, in sea trials, the conditions under which it occurs are seldom well defined. There is the further problem of accounting properly for the effects of modifying the test fluid itself either by a change in state point or by the addition of an additional liquid solute such as a long chain polymeric molecule or finely divided particulate matter. Underlying all these considerations is the ultimate goal of extrapolating laboratory findings to representative field conditions; in the present context, these are the various conditions of the marine environment. This specific point was addressed briefly in the concluding discussion on cavitation inception of the 16th conference in which the onus of reporting progress towards this goal was laid upon the present authors. It would indeed be gratifying to report to the present conference that our experimental techniques are now sufficiently advanced to simulate properly all of the important prototype conditions even if we had precise knowledge of them. This is, regrettably, not yet the case, but there have been nevertheless solid advances in certain areas of cavitation inception research which make one hopeful for the future. We have selected three such areas to report on to the present conference; viz, surface inception, vortex cavitation and scaling, and the effects of polymer additive on inception. In addition, we refer briefly to current methods of observation/measurement of cavitation nuclei as this is a subject of paramount importance to the cavitation process itself and also because we suspect such measurement will become an important part of laboratory testing in the near future.

In the material to follow we have tried to emphasize the phenomena and techniques themselves leaving to a future occasion a full assessment of inception scaling theories. We have not attempted to be encyclopedic in coverage as there are recent excellent texts and survey articles, e.g. Arndt (1971), Eisenberg (1969), Eisenberg and Tulin (1961), Knapp *et al* (1970), Robertson and Wislicenus (1969) Grein (1973) which cover the field, and we should also state that in so doing any serious omissions we may have made are not intentional!

2. Cavitation Inception on Smooth Surfaces.

2.1 By this is meant surfaces whose boundaries have a continuously turning tangent plane and which otherwise are "hydraulically" smooth. The inception of cavitation on such a surface appears in many different physical forms even for a given body profile. The most widely tested single body profile is probably the ITTC standard headform (Lingren and Johnsson, 1966). The results of these internationally known round-robin tests demonstrated that great differences in cavitation inception index were found in different test facilities even on the same identical body and the physical form taken by the cavitation at inception often differed greatly. These at first surprising results have stimulated a great deal of additional research. A follow-up study by Johnsson (1969) sharpened these points; reproduced here (Fig. 1) is his comparison of nine photographs of cavitation inception on the standard body in six different facilities in which it may be seen that numbers 4, 5, 9 exhibit a similar form of attached cavity at inception (without transient precursers) and in the remaining cases inception appears in the form of traveling macroscopic bubbles. In the same article it is suggested that some of the observed discrepancies could be due to a laminar separation on some of the bodies used. Subsequent oil film dye experiments are then described which indeed showed a laminar separation up to speeds of about 4 m/s. The importance of clarifying these possibilities was further stressed (Eisenberg, 1969). Rather similar observations were made at the same time on another modified ellipsoidal body having a deeper pressure minimum (Peterson, 1969). Again laminar separation at lower speeds was observed with oil film techniques but this did not play a role at the higher speeds of cavitation testing. The cavities observed under these conditions at inception were typically intermittent traveling bubbles and another consisting of a fixed spot cavity originating on the body surface at or near the location of Cp_{min} (similar to that of No. 6 in Fig. 1).

In summary we find from these and other studies (van der Meulen, 1972, Arakeri, 1971, 1973) that typically there are three types of cavitation at inception on smooth bodies*; (1) traveling, growing bubbles (originating from a position near Cp_{min}), (2) fixed 'spot' nucleation sources near the position of Cp_{min} behind which is a region of attached cavitation, and (3) attached "sheet" cavities. All of these forms may exist simultaneously. The "sheet" may be glossy smooth or, in some circumstances, may consist of many small transient bubbles. It seems appropriate here in view of the foregoing discussion to mention that traveling bubble inception has received most attention in recent years and it is to this mode that most inception scaling theories have been directed (see, for example, the article by Holl in Robertson and Wislicenus). Not much is known of the spot type of inception although

*Assumed to be in two-dimensional flow.

Peterson's (1969) suggestion of a local nucleating source seems very plausible. The sheet or band cavitation also often observed is, we believe, due to the presence of laminar separation or is even perhaps the location of a turbulent transition. It is to be expected that incipient cavitation indices of these various forms will differ greatly* particularly if a laminar separation is involved as such a separation is invariably downstream of Cp_{min}. Which of these forms or modifications thereof is dominant in any particular situation depends upon the entire environment of the liquid flow. This includes all aspects of the viscous flow around body itself together with that of the sources for the nucleation of cavitation. In the next section we summarize briefly methods of observing the real fluid flow around bodies. Following this we review methods of cavitation inception determination and conclude with brief comments on recent experimental findings that bear on these points.

2.2 Real fluid liquid flow observations and measurement methods. Of particular concern here is the flow of water at Reynolds numbers typical of laboratory experiments (up to approximately 10^6). We are then primarily concerned with thin boundary layers. The main feature of such boundary layer flows in the present context is the possible existence and structure of a laminar separation bubble or of a transition from laminar turbulent flow. But because of the thinness of the region of interest, methods depending upon "marking" the fluid by particles, dye or small bubbles become very difficult to apply. Recourse must be either to indirect methods reflecting events within the viscous flow itself or to more recent emerging techniques some of which are yet to be proved. We tabulate below these principle methods:

TABLE I – LIQUID BOUNDARY LAYER FLOW VISUALIZATION AND MEASUREMENT METHODS

1.	Oil Film B. L. Visualization	Difficult to use at high flow speeds, careful techniques needed.	Loving, et al (1959), Etter (1968), Casey (1973)
2.	Fluid Dye and Related Methods	Requires injection, suitable for low flow speeds (~< 3M/s), location and tech. important. Best for large scale separation.	Johnsson (1969), Werlé (1973)
3.	Thermal B. L. Visualization	Use Schlieren or shadow-graph tech. Requires slight temp. contrast by heating or cooling.	Arakeri (1973), Arakeri and Acosta (1973)
4.	Discrete Pressure Transducers	Suitable mainly for transition determination.	Arakeri (1974)
5.	Discrete Flush Hot Films	Suitable mainly for transition.	
6.	Scattering Laser, Velocimeter	Provides direct measurement of velocity. In principle can detect transition.	George (1973), Barker (1973), (1974)

*Even excluding gaseous cavitation.

The first two of these have been well-developed and of these the oil film is the more suitable for water tunnel use as dye disperses rapidly at speeds typical of usual operations (> 3 M/s). The oil film technique is very useful in hydrodynamic applications particularly for detecting regions of laminar separation and it is probably the only suitable technique for thin hydrofoils. Casey (1973) has obtained good success in observing the laminar separation on a 50 mm NACA 0015 hydrofoil at speeds of 8 M/sec using transmission oil as the medium with carbon black added for contrast. The Schlieren method is readily adapted to hydrodynamic use. It is controllable to some extent and is more sensitive than oil film techniques showing some detail of the reattachment process behind a laminar separation (Fig. 2). It has the advantage that it can be used with short-duration flash, spark or even laser discharges to show the simultaneous development of cavitation and the boundary layer as is shown in Fig. 3. The method must be used with some care however or the thermal gradients which must be imposed may alter the basic viscous flow. This is more of a risk for transition than separation (see for example Wazzan, et al, 1970, Lowell and Reshotko, 1974) but sensitivity of the method is sufficiently great and the requisite temperature differences so small (~2.5° F) that the effect is negligible on practical bodies. The principle difficulty of the method is that internal heat transfer must be provided.

Items (4, 5) are techniques in current use especially for transition detection; they are expensive and time consuming and have defect of requiring application at discrete points. The scattering laser velocimeter has had a profound effect in hydrodynamic research offering as it does the most satisfactory non-intrusive, velocity-vector measuring system to date. It is particularly suitable for routine turbulence measurements (George, 1973) for example, and it can be used to probe into flows which would otherwise be disturbed by the instrument. Barker (1973) has provided an inexpensive design and with an elaborate traversing mechanism for water tunnel surveys (1974) is able thereby to study the structure of trailing vortex wakes and to measure velocity profiles around hydrofoils just outside of the boundary layer. It appears feasible to determine the gross characteristics of the surface boundary layer by such a technique although to our knowledge this has not yet been done.

2.3 Methods of inception observation and determination. Historically, the existence of cavitation was first observed with the unaided eye under natural illumnination. Erratic and often unreproducible results have led to such visual observations being carried out under stroboscopic illumination at a convenient repetition rate (say 100 Hz) which considerably diminishes the differences between different observers (Johansson, 1972). Yet there are more important distinctions to be made beyond that offered by such a simple observational technique; namely, a clear definition or description must be made of the type and location of the incipient cavitation to be observed and the observational technique employed must be selected accordingly. The various forms of cavitation inception previously mentioned are depicted in Fig. 4. Clearly, the location on the body is drastically different for these various manifestations as is the physical appearance itself. Peterson (1972) makes a further distinction in regard to the traveling bubble inception type as to whether it is of the 'explosive' (or vaporous) type or is gaseous as there appears to be significant differences in the level of acoustic output for the two types. This is another important aspect of inception determination since acoustic inception measurement can be a valuable unbiased, automatic procedure. The sound pressure level and perhaps spectrum at some location in the test facility have been often measured as a function of cavitation number to determine inception and even to infer the type of developed cavitation (see Wood, 1969, for example). Such measurements are often inconclusive, however. Recently, a refinement was introduced by Scheibe (1966) in which the collapse rate of individual cavitation bubbles on the test body itself is measured as a function of cavitation number, the transducer being mounted within the test body. This approach has been vigorously pursued by Brockett (1972) who concludes that the method is more reproducible than visual determination and can be readily adapted for towing tank work where direct observation is not feasible. The method is not without complications and limitations but it appears well-suited for bubble inception determination on bodies of sufficient size. Beyond that, the principle of cavitation occurrence counting on a particular type of a body of revolution has been proposed as a diagnostic device to determine the nucleation characteristics of the water actually used in towing tanks or water tunnels (Silberman, et al, 1973, Silberman and Scheibe, 1974).

Whichever the method of inception determination, there is the further question of selecting the threshold level and the operational means by which this level is achieved. These points have all been discussed in the literature to some extent but there does not now appear to be any uniformity in the methods used although there is a useful and growing tendency to report more and more of the test conditions and procedures under which the experiments are made.

We now tabulate for convenience some representative methods, of inception observation:

TABLE II – SOME METHODS OF INCEPTION DETERMINATION

Method	Type Observed	Threshold	References
Visual (strobe)	Sheet, Bubbles Spots	Judgement (often sheet cavitation occurs with no precursors)	Johnsson (1969, 1972) van der Muelen (1972) Arakeri (1972), Peterson (1972)
Laser Beam Scattering (Acoustic check)	Bubbles (probably)	- -	Ellis (1967, 1968, 1970)
Light Beam Interruption	Bubbles	50 events/sec	Keller (1973)
Acoustic (Hydrophone inside test body)	Vaporous Bubbles	one event/sec one event/sec ~ one event/sec	Brockett (1972) Peterson (1972) Silberman, et al (1972)
Acoustic (Press. transducer or hydrophone in tunnel circuit)	Usually unknown unless visual check	Judgement (from resolution against background)	Wood (1969)

2.4 Methods of nuclei measurement. The role of cavitation nuclei in experimental work in cavitation inception has been the subject of intense interest and even controversy since, until the last few years, methods of observing or measuring them in experimental situations have not been available. Much progress in this direction has been made in recent years and this is summarized in the exhaustive review by Morgan (1972). In this review (unfortunately not generally available) various photographic (including conventional photography, microscopy and holographic photography), acoustic and light scattering techniques are described and evaluated. The purpose of this section is to draw attention to this progress and to report briefly on developments subsequent and parallel to those noted above.

In this latter respect it is of interest to note that there are very similar measurements problems connected with the observation of and characterization of populations of atmospheric aerosols which form the "nuclei" for various meteorological processes. The approach on the whole is similar to that in hydrodynamics except that acoustic methods are inapplicable. Generally the approach is to determine the distributions of particle sizes by single particle counters (similar in principle to that used by Keller, 1973) and total concentrations by light extinction or light scattering methods. These latter depend upon the optical properties of the aerosols and may not be very well known. These types of measuring problems are discussed by Friedlander (1971), and Hodkinson (1966) gives a very thorough and lengthy review of light extinction and scattering principles. He includes descriptions of several types of instruments amongst which is the design of an extinctiometer for hydrosols (in this case liquid suspensions of particulates less than about 10 micrometers). There has been considerable development of single particle counters into a number of commercially available instruments as discussed in the book by Mercer (1973). Particles in size down to 0.25 micrometers are readily detected but these machines are not readily adapted to water tunnel research except in principle because of the difficulty in a tunnel of prescribing a definite volume in which the scattering is to occur.

More recently Hammitt et al (1974) have reviewed their work on two single particle counters; the Coulter counter, and the light scattering technique of Keller. The Coulter counter must interfere with the flow (see Morgan Ibid. for details) and on the whole is not as satisfactory as the light scattering technique (Keller et al, 1974). Hammit (1974) suggests that the Coulter counter may find application in liquid metal cavitation research where optical techniques are ruled out.

The rather novel and ingenious indirect approach proposed by Silberman and Scheibe for the inference of nuclei populations by cavitation occurrence counting has already been mentioned. A key feature of this proposal is that inception should be of the traveling bubble type and uninfluenced by the viscous flow of the body itself, so that the characteristics of the water and the nuclei it contains may be inferred.

Additional work on the use of holographic techniques has been reported by Feldman and Shlemson (1972) with results similar to that reviewed by Morgan. There is also an evaluation of three different optical methods now underway* which should be of great help in defining a laboratory system. Finally, it may be mentioned that there is considerably more knowledge concerning nuclei, or at least microbubbles, in the natural ocean environment (Morgan Ibid.; Medwin, 1970) than formerly available.

2.5 Some recent work. We mention here some recent inception measurements on two different bodies which bear out the importance of experimental technique and the environmental effects of the flow (Arakeri and Acosta, 1974). The first of these consists of inception measurements carried out by NSRDC on a modified ellipsoidal head form (Brockett, 1972). This same head form was subsequently tested in the Caltech facility and the comparative results are shown in Fig. 5 in which it can be seen that there are significant differences. The various physical forms taken by the cavitation at inception and sketched in Fig. 4 have already been mentioned. Some of the differences here are due to this; the NSRDC data points (only a few of these are shown) are primarily of the bubble type and the majority of Caltech inception observations are for band or sheet cavities. There is a further difference also since a laminar separation was not present for any of the NSRDC data points whereas this feature persisted up to 25 ft/sec in the Caltech facility to be gradually replaced thereafter it is thought by turbulent transition. The correspondence of the inception points with the pressure coefficients at predicted points of transition is

*Private communication with Dr. F. Peterson.

indeed very suggestive of this. At higher speeds the fixed spot inception form emerges and these data seem to agree fairly well with the NSRDC experience.

A rather different type of result is shown in Fig. 6 which shows the effect of a boundary layer trip on the well-tested hemisphere body. By this means, the pre-existing laminar boundary layer is forced into transition – or at least the laminar separation is caused to disappear – and inception indices (visually called under strobe illumination) become drastically reduced. In fact, except for an occasional traveling bubble, it was not possible to obtain cavitation on this head form even at the choked tunnel limit for the highest velocities of the tunnel.

We mention these results to emphasize again the important effect that can be played by the facility and test technique. The physical factors that can lead to a modification of the basic real fluid flow around the body have already been mentioned. One of the basic hydrodynamic reference quantities in this real fluid flow is the critical Reynolds number above which transition occurs without a laminar separation. For reference these are estimated and tabulated below by the Smith and Gamberoni method using the conservative transition parameter of e^7 for several of the commonly used test bodies*:

TABLE III – CALCULATED ESTIMATES OF THE CRITICAL REYNOLDS NUMBER
(Based on freestream velocity and maximum diameter)

Body	Reynolds No. (critical)
Modified Ellipse [see Peterson 1969, Brockett 1972]	0.46×10^6
1.5 Cal Ogive	0.64×10^6
Modified Ellipse [I. T. T. C. Test Body, Lindgren and Johnsson, 1966]	1.2×10^6
Hemisphere – cylinder Body	5×10^6
Flat Plate (Spangler & Wells, 1968)	5×10^6

From the preceding discussions it seems very clear that much of the data reported on cavitation inception arises from very different test, hydrodynamic and nucleation environments. It may be premature, but one can be hopeful that techniques under present development described herein and elsewhere at this conference will be able to resolve these various effects and lead to the predictive ability mentioned at the beginning of this review.

3. Vortex Cavitation Inception and Scaling. When one thinks of vortex cavitation, he most naturally visualizes the orderly trailing vortex cavities which are observed

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*Calculated by Dr. V.H. Arakeri.

in the vortex cores downstream of lifting surfaces and propellers. The inception of cavitation related to such tip-vortex flows is one of the topics reviewed here. As we have said, such cavitation is commonly found in the flow around propellers, pumpjet blades and hydrofoils. Of course, the above flows are not the only cause of cavitation which is associated with intense vorticity in a flow. Other sources which arise primarily because of viscous effects are associated with secondary flows in the boundary layer and tip clearance flows in turbomachinery. Other vortex flows arise in turbulent boundary layers and in free shear layers behind bluff bodies or as a result of orifice flows. These flows cavitate because of pressure fluctuations in turbulent eddies, and they do not often exhibit any well-defined sense of order to the observer. Perhaps one of the chief attributes of these forms of cavitation is the fact that, except for boundary layer and tip clearance flows, inception is observed in flow regions which are somewhat removed from the local flow close to the solid body which gives rise to its existence. All of these forms of vortex cavitation have been under investigation for many years. For a thorough review of past, as well as fairly recent progress, the reader is referred to Arndt (1971), and Holl, Arndt, and Billet (1972). On this occasion, we shall restrict ourselves to the latest developments known to us.

In order to define the scope of this discussion, some further classification of vortex cavitation is helpful. For example, with flows involving long trailing vortices, we will consider two classifications: hub-vortex cavitation, and tip vortex cavitation. In this review, we will confine our attention to the first category simply because this phenomenon is currently under investigation. For cavitation in turbulent shear layers, we may note that the effects of single and distributed roughness elements is still a matter of practical significance, and further work should be carried out to enhance our knowledge of these effects. Two new references on the subject of surface roughness effects since the 16th ATTC are Arndt et al (1972) and Bohn (1972). The major new information is that for isolated roughness the cavitation number can be expressed in the form

$$\sigma = C_1\left(\frac{h}{\delta}\right)^m \left(\frac{\overline{U}\delta}{\nu}\right)^n$$

where h is the height of roughness, δ the boundary layer thickness, and $\overline{U}$ the velocity at the edge of the boundary layer. This correlation for various types of roughness elements is shown in Figure 7. Applications of this equation, together with the law for distributed roughness $\sigma = 16\,C_f$ are presented in references cited above. The effects of clearance flow vortex cavitation has not been a recent research topic. Although this form of cavitation is of continuing interest because of its noise and damage potential, its occurrence is investigated visually on an ad hoc basis in the course of rotating machinery design and testing. Finally, we will need to consider further the question of incipient cavitation in free shear layers as they occur downstream of bluff bodies and submerged jets. These items are of active interest in connection with the effects of polymer additives on inception, and they will be considered below in the section on polymers. As a result, it appears that since the last ATTC review, the chief new work which requires reporting now is an updating of progress on hub vortex cavitation.

As a preliminary to our discussion of hub vortex cavitation, some description of its main features may be useful. As its name implies, this form of vortex cavitation occurs behind the hubs of rotating propellers and pumpjets. At present, it is believed that three mechanisms may be associated with its occurrence. One of these depends upon the secondary flow generated by the action of blade roots in the non-uniform velocity profile in the boundary layer of the body. As is well known, this is a secondary flow which causes a vortex to wrap itself around each blade root with its two ends trailing downstream. Another secondary flow effect which is present in some classes of turbomachinery is a general circulation in a rotating blade row which is caused by an azimuthal pressure gradient which points from the suction side of one blade to the pressure side of the next blade, and by the relative accelerations in the rotating coordinates in which this flow is seen to act (Lakshminarayana and Horlock (1973)). Vortex filaments from these secondary motions then contribute to a general twisting into a "rope" as they are convected downstream behind the propeller. Another mechanism may be due to the fact that each blade of a thrusting propeller or rotor is unloaded at its root with a consequent steep radial lift gradient in this region. As a result, additional vorticity is shed into the hub region behind the propeller which contributes to the swirl caused by the secondary flows noted first. The resulting vortex downstream of the propeller hub provides low pressures in the flow so that cavitation inception is ordinarily observed to take place in the trailing vortex core.

As is generally the case with cavitation inception for other flow types, the inception process is intimately related to the noncavitating flow structure. Thus, in view of the preceding discussion, it is evident that the Reynolds number is of importance. One might also expect the thrust or torque coefficient to have some bearing on the inception process, although its relative importance is not known at this time. In addition to these rather large scale aspects concerning the flow as a whole, there are other effects which can have an important influence on the inception process. For example, the air content in the flow has a pronounced effect. Dissolved gas will diffuse into the core region and bubbles will migrate to the center of the swirling flow. Vortex bursting is another effect which can have a marked influence on inception because vortex bursting lessens the intensity of the low pressure in the core.

Thus far, we have emphasized the role of rotating blade rows in the discussion of vortex cavitation. Of course, stator rows can also act to produce hub vortices. However, from the preceding discussion, stator rows are probably not fully equivalent to rotor rows. The simplicity of stator rows has led to the design of an apparatus for fundamental studies of hub vortex flows in wind tunnels and cavitation inception in hub vortices in water tunnels. A schematic diagram of this vortex generator is shown in Figure 8. It has been designed for use in the 12-inch water tunnel. The generator consists of a set of eight adjustable swirl vanes assembled on a hub section as illustrated. The blades have two degrees of twist, increasing from tip to hub. The blade angles can be adjusted from 0 to 4 degrees at the tip. The conical tip of the hub has five pressure taps, including one at its centerline. These taps are used to measure static pressures on the cone and as dye injection ports. As illustrated in Figure 8, this apparatus has been built to fit into the 12-inch water tunnel at the Garfield Thomas Water Tunnel (GTWT). For wind tunnel testing the entire upper horizontal leg of the 12-inch water tunnel is mounted in the test and diffuser sections of the 48-inch wind tunnel. The settling section of the water tunnel is joined to that of the wind tunnel by an appropriate sheet metal transition. By this means, it is possible to test in air at speeds up to 325 fps and in water with speeds up to about 60 fps. Thus, water and air tests are conducted over a common Reynolds-number range. Air testing offers the advantage of experimental convenience for many measurements in the basic non-cavitating flow which are somewhat difficult in water. In particular, wind tunnel testing has been found helpful for studies of vortex bursting and its effects on the minimum pressure in the vortex cores and for assessing the influence of various aspects of the swirling flow, and the hub boundary layer on bursting. One observation which is not particularly new, but which is worth emphasizing again, is the fact that premature vortex bursting often occurs when even a minature probe is put in the core. For this reason, core pressure measurements are made from the pressure tap at the tip of the hub.

At this time, our understanding of hub vortex cavitation is not complete and investigations continue. For example, we do not have an adequate description of vortex bursting. Nonetheless, some results on desinent cavitation are shown in Figure 9. Some general conclusions which are now available can be summarized as follows:

1. $C_p|_{min}$ for the hub vortex is strongly dependent on Reynolds number.
2. In the absence of vortex bursting, $C_p|_{min}$ decreases with increasing Reynolds number.
3. Vortex breakdown raises the absolute pressure on the cone tip.
4. The pressure at the cone tip is sensitive to upstream flow conditions.
5. Swirl angle and adverse pressure gradients are important parameters in hub vortex breakdown.
6. The role of Reynolds number in vortex breakdown is not clear.
7. Gaseous cavitation appears to correlate reasonably well with calculated results based on the equilibrium theory.

From the foregoing, it is evident that much remains to be done before a scaling theory for desinent hub vortex cavitation will be available for reliable predictions of hub vortex cavitation occurrence for full-scale ships. Results to date indicate that vortex bursting is important for cavitation inception. In order to scale test results to full-scale predictions, further information on the effects of Reynolds number, possibly on thrust coefficient, and relative swirl angle are required. Previous work on tip and hub vortices needs to be extended to include secondary flow effects. For example, flush inlet design cavitation inception could be sensitive to such effects.

4. Effects of Polymer Additives on Inception*. It has been known for some time that drag-reducing macromolecules inhibit the inception of cavitation in a given flow situation. For example, Ellis (1967, 1968, 1970) conducted a series of experiments to explore the effect of high-polymer substances on both cavitation inception and its appearance on a hemisphere-nosed cylindrical body in a blow-down water tunnel. Using a 0.635 cm. dia. stainless steel test body, he detected the inception of cavitation in two ways. A laser beam was adjusted to just graze the surface of the hemisphere nose in the region where cavitation first appears. Light scattered by the cavitation bubbles was detected by a photo cell sensing light at about 90° from the laser beam direction. This method of cavitation detection was checked by acoustic observation, and extremely close agreement was obtained.

Tests were made with water (passed through an 0.4μ filter), 50 and 100 ppm poly (ethylene oxide) and a suspension of alga, Porphyridium aerugineum. All tests were made with water containing the same amount of dissolved air, 17 ppm and the following inception data were obtained (averages of 4 runs):

	Tunnel Velocity m/s	Inception Cavitation Index=$(p-p_v)/\rho V^2/2$
Water	12.55	.73
20 ppm Polyox	13.40	.50
50 ppm Polyox	14.18	.39
100 ppm Polyox	13.70	.41
Algae	12.88	.66

Thus, it can be seen that the polymer content of the water has a large effect on the cavitation inception point. This may be a factor in explaining the large differences in inception index found in the I.T.T.C. tests (Lindgren, 1966), since unknown amounts of algal or bacterial polymer might have been present in the water.

The initial appearance of the cavitation bubble is also changed by the presence of high-polymer. There also seems to be a noticeable difference (Hoyt, 1966) in the appearance of steady-state cavities in flows containing high-polymer solutions compared with observations at the same cavitation index in pure water. The polymer-solution cavity is more striated, and appears to collapse less violently than the water cavity; high frequency-response pressure measurements confirm the diminishing of the intensity of fluctuations. Thus, a change in external appearance of cavitation may

*The authors are indebted to Dr. Jack Hoyt (1974) for a major part of the material presented in this section.

be expected when known (or unknown) contamination of the water tunnel by high-polymer substances occur.

The changed appearance of cavities in polymer fluid flow as compared with pure water has been beautifully shown by the photographs of Brennen (1970) who studied the flow over cavitating hemispherical head shapes. Brennen found that all polymers tested-poly (ethylene oxide), guar, polyacrylamide, and CTAB-napthol - had pronounced effects on cavity appearance. There is as yet no explanation for these changes in the flow behavior. Ellis and Ting (1970) for example, could find no difference in the collapse-time of a spark-generated single bubble in either water or several types of polymer solutions.

Although an early report (Anon 1964) indicated lowered erosion due to sustained cavitation in polymer solutions, Plesset has been unable to confirm this, see Hoyt (1967), at least with a magnetostrictive transducer device in polymer solution concentrations of most interest in friction reduction. The magnetostrictive technique is not necessarily representative of cavitation erosion in flow situations and further study is needed to clarify whether or not erosion is affected by the use of polymers in a flowing stream.

Recent cavitation studies in polymer solutions have centered on jet cavitation, cavitation inception on rotating disks and propellers, and water tunnel studies of hemispherical nose shapes. Jet cavitation studies Hoyt (1971, 1973) show that the cavitation index can be reduced to half the previous value when small quantities of poly (ethylene oxide) are present in the flow; amounts as small as 1/2 ppm were detectable by this technique. We note that inception is delayed even though the surface tension of water is drastically lowered by these polymers.

Walters (1972) has shown a similar lowering of cavitation inception index on a disk, and White (1971) found that the cavitation bubble production by a small propeller, observed by counting bubble collapses, was greatly reduced by 25 ppm or more poly (ethylene oxide). Both Walters and White noted that the higher frequency noise content (5-15 kc) of the bubble collapse spectra was diminished. Under very intense cavitation, the polymer solution produced a higher level of radiated noise at high frequencies than water. Acoustically produced cavitation inception was also retarded by the presence of polymer, Darner (1970).

Van der Meulen (1973) has shown that cavitation inception on a hemispherical-nosed stainless steel body in a water tunnel is greatly reduced by the presence of poly (ethylene oxide), while a teflon coated body showed a much smaller effect. In other work, Huang (1971), noted that the cavitation inception reduction with poly (ethylene oxide) was much smaller when a large (4-inch diameter) model was used in a water tunnel. No theoretical approach to cavitation in polymer solutions has been given except a note by Lumley (1972).

The foregoing results have been obtained from both blow-down and closed-circuit water tunnel experiments. Recent work involving closed-circuit tunnels at the GTWT has shown that the effectiveness of a given concentration of polymer in the water can be reduced by continual mechanical effects of the pumping machinery and other flow impediments which are always present in such tunnels. As a result, the state of the polymer must be monitored continuously in order to obtain reasonably reproducible data in the course of drag reduction or cavitation inception tests in closed-circuit tunnels. Presumably, in blow-down tunnels the polymer solution should be checked for degradation between each run, unless experience indicates that degradation will be relatively small for several runs.

In order to permit continuous monitoring of the state of a polymer solution in a closed circuit tunnel, Berman (1973) has devised a method which uses a friction tube as illustrated in Figure 10. One can also monitor the polymer state by using drag measurements from a standard "drag-reduction" body. In principal, the drag measured on this body can also be correlated with the results of the friction tube, although so far, attempts to do this have not been wholly successful. For example, in an experiment with 20 ppm polyox showed 100 percent drag reduction at all Reynolds numbers. After one hour of tunnel operation, the friction tube showed large polymer degradation and little drag reducing capability within the range of tube Reynolds numbers. However, maximum drag reduction can still be obtained at sufficiently high values of shear rate. Five hours later, the fluid in the tunnel was essentially water, according to data from the friction tube. In contrast, the drag body showed some residual drag reduction four days after this polymer solution had been put into the tunnel. Figure 11 presents data on cavitation number reduction obtained for a series of hemispherical noses in dilute polymer solutions. The data tabulated above have also been plotted on this graph. These data are in general agreement with the trends previously reported by Huang (1971). The general trends observed in the GTWT work can be summarized as follows:

1. There is a definite trend of reduced polymer effectiveness on percent reduction in desinent cavitation number as model size increased.
2. For the 20 ppm polyox solution the maximum desinent cavitation inhibition was always observed when the solution was fresh.
3. Both 8.0-inch diameter hemispheres and ellipsoidal noses were tested. Neither showed a significant effect due to polymers.
4. For the same percentage of effective drag reduction, the percentage of cavitation inhibition on a particular nose geometry increased as velocity decreased.
5. At low velocities the trend in (4) is obscured by gaseous cavitation.
6. Results to date indicate a possible correlation between effective drag reduction and cavitation inhibition.

Some confined jet studies have also been undertaken at the GTWT in order to examine further the influence of polymer additives in free shear flows. Cavitation studies are presently being made in a confined jet which is produced by inserting a

2-inch diameter orifice plate in the test section of the 6-inch cavitation research tunnel. Desinent cavitation is observed visually and with high-speed motion pictures. Extensive hot -film measurements of turbulent fluctuation within the jet shear layer have commenced. Mean flow velocities in the layers have been as high as 15 fps. It is planned to correlate these measurements with photographically observed jet spreading and unsteady cavitation phenomena. Measurements at higher mean flow velocities will also be attempted.

Figure 12 shows some preliminary data from this work. The GTWT result is compared with data from Hoyt (1973) which shows that cavitation suppression due to polymer addition is comparable in the two situations — one involving a free jet, and the other a confined jet. It is known that intense pressure fluctuations which are thought to induce cavitation are associated with the initial development of turbulence near the nozzle lip. Evidently, this effect is changed about equally by polymer addition in the two situations of the comparison. Further clarification of these results is hoped for as the research program progresses.

Acknowledgment

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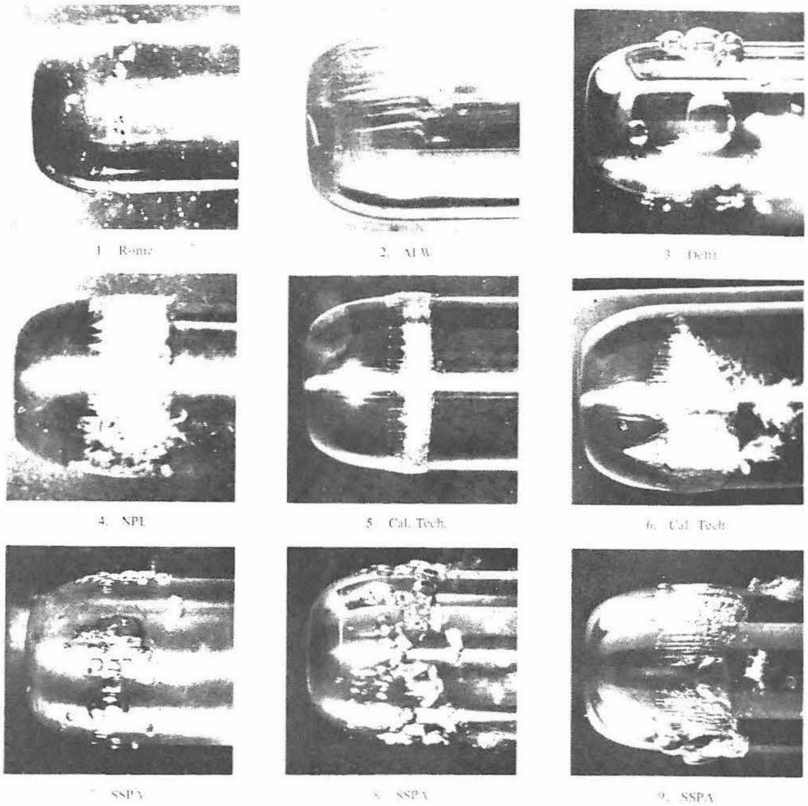


Fig. 1. Photographs of Incipient Cavitation on the ITTC Head Form in Various Facilities (Johnsson, 1969).

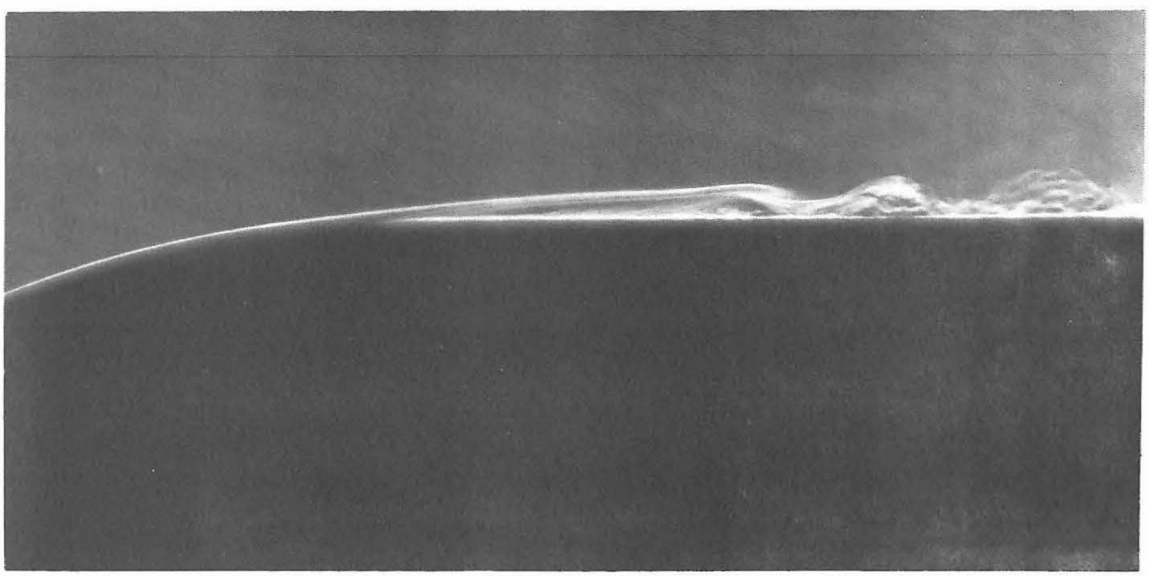


Fig. 2. Schlieren Photograph Showing Separated Flow Past a Hemisphere Body at a Reynolds Number of about 10^5 The Body Diameter is Two Inches (Arakeri, 1972).

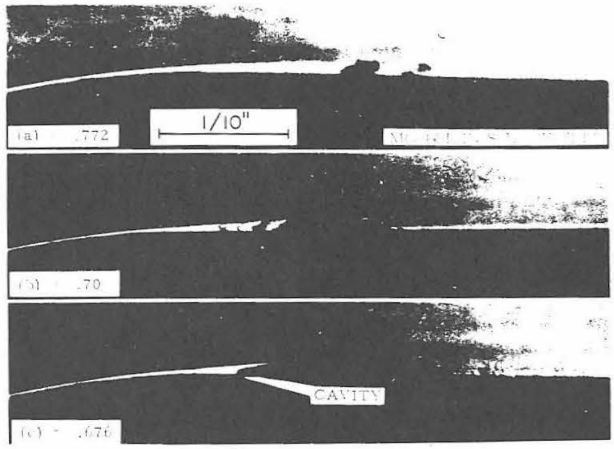


Fig. 3. Schlieren Photographs on a Hemisphere Body Showing Location and Development of Incipient Cavitation in the Separated Boundary Layer. The Reynolds Number is 6.7×10^5 (Arakeri, 1972).

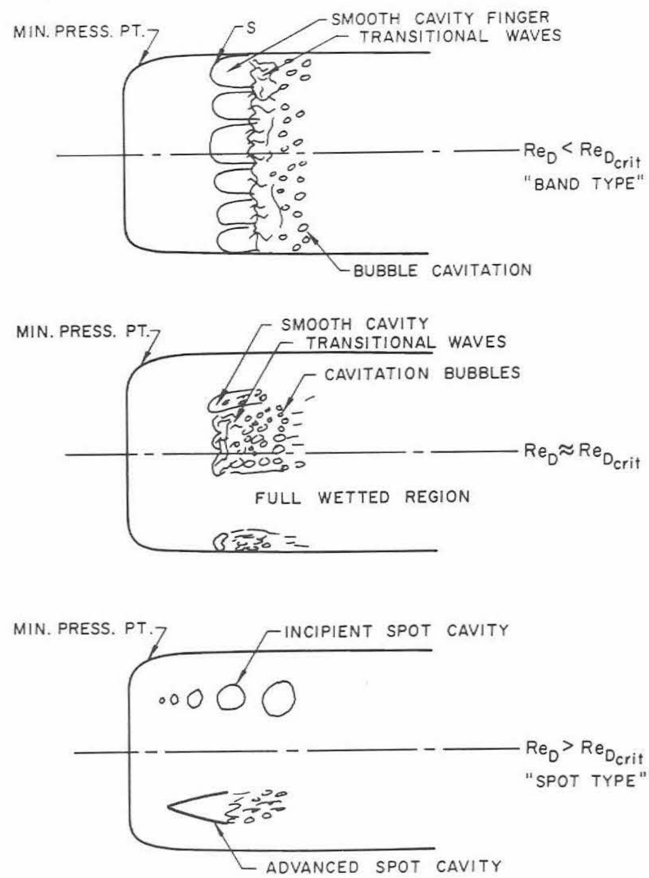


Fig. 4. Sketches of the Location and Type of Cavitation Observed on the Modified Ellipsoid Body for Various Reynolds Numbers. (Test Body Courtesy Dr. F. Peterson NSRDC)

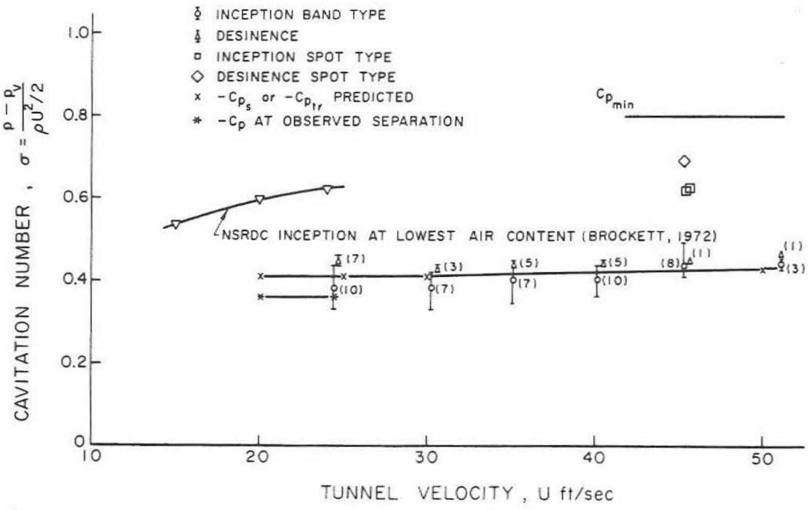


Fig. 5. Inception Data on the Modified Ellipsoid Body of Fig. 4. The Air Content for the CIT Data was 10.4 PPM. (Arakeri and Acosta, 1974).

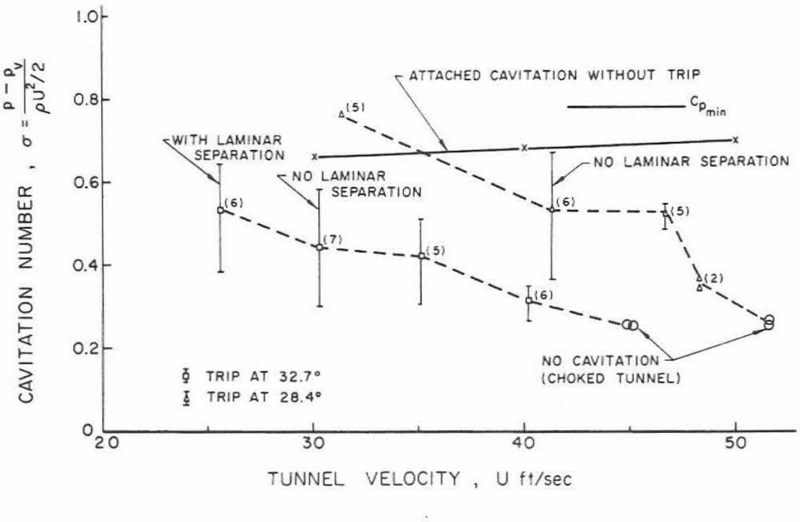
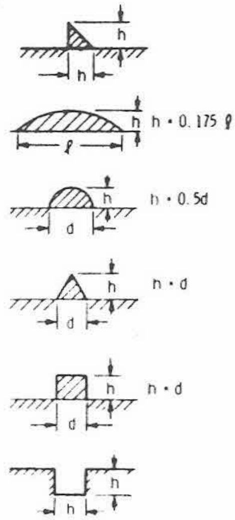


Fig. 6. Inception of Cavitation on a Two-Inch Hemisphere Body with Boundary Layer Trips. (Arakeri and Acosta, 1974).

SYMBOL	IRREGULARITY	FLOW DIMEN-SIONS	DATA SOURCE	a	b	c
△	TRIANGLES	TWO	HOLL, 1960	0.361	0.196	0.152
○	CIRCULAR ARCS	TWO	HOLL, 1960	0.344	0.267	0.041
▲	HEMISPHERES	THREE	BENSON, 1966	0.439	0.298	0.0108
●	CONES	THREE	BENSON, 1966	0.632	0.451	0.00328
□	CYLINDERS	THREE	BENSON, 1966	0.737	0.550	0.00117
⊔	SLOTS	TWO	BOHN, 1972	0.041	0.510	0.000314



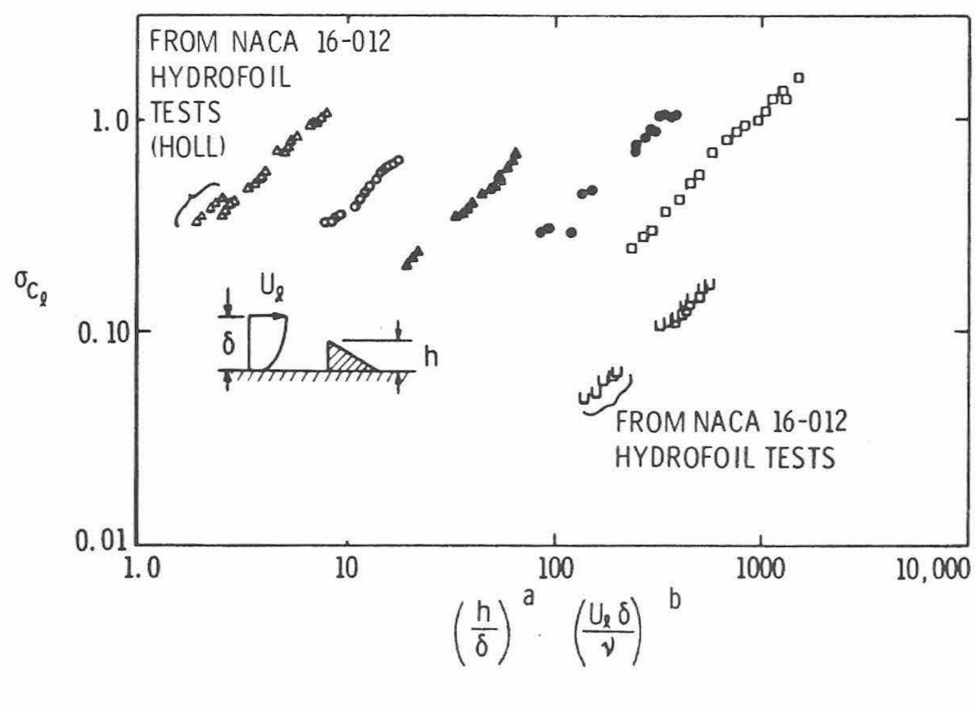


Fig. 7. Power Law for Isolated Irregularities.

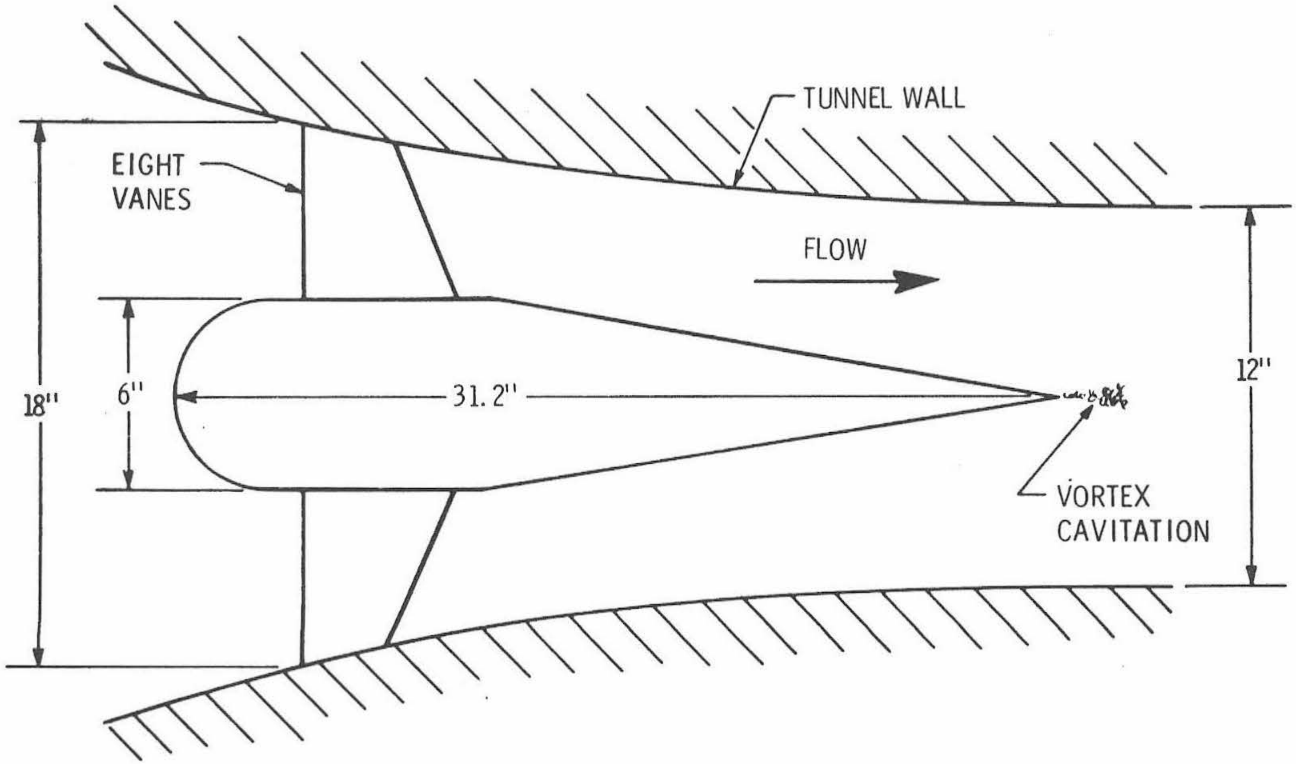


Fig. 8. The Vortex Generator

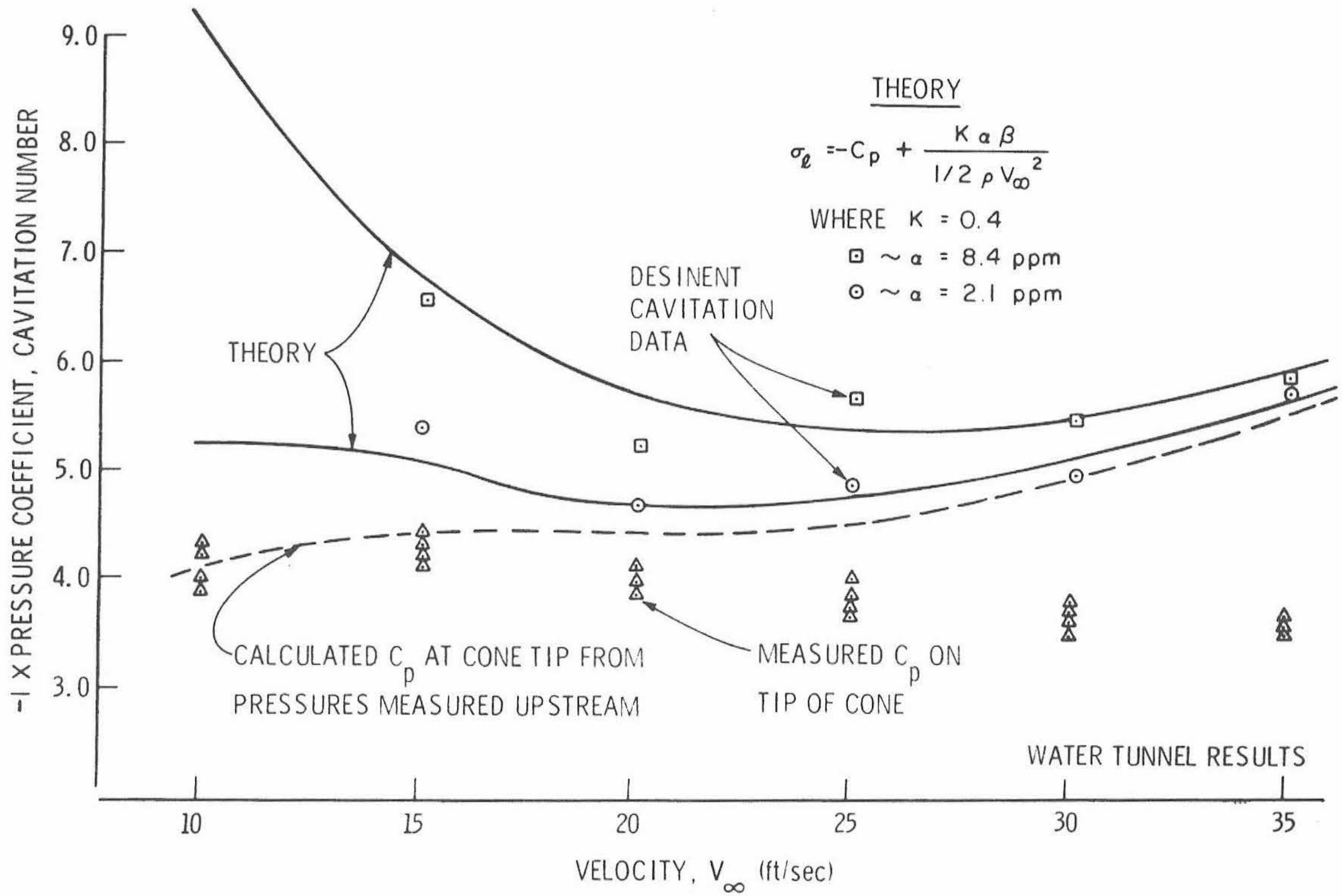
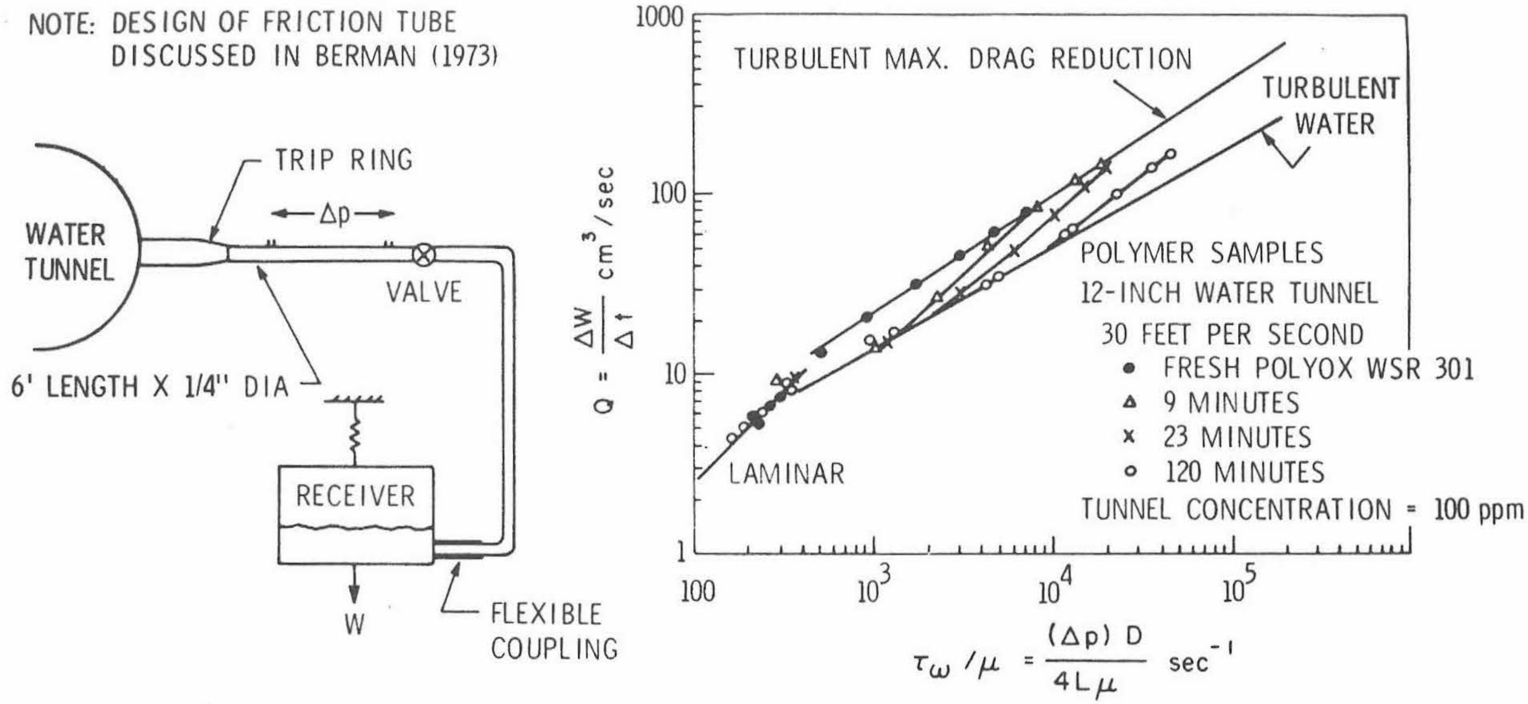


Fig. 9. Comparison of Cavitation and Pressure Data for a Hub Vortex (5° Blade Angle at Hub).



OPERATING PROCEDURE

1. PRESSURE DIFFERENCE IS CREATED BETWEEN TUNNEL AND EMPTY RECEIVER
2. FLOW IS INITIATED BY OPENING VALVE; PIPE PRESSURE DROP (Δp) AND RECEIVER WEIGHT (W) ARE CONTINUOUSLY RECORDED. RUN IS TERMINATED WHEN RECEIVER PRESSURE EQUALS TUNNEL PRESSURE (TYPICAL RUN TIME ~ 40 SECONDS)
3. WALL SHEAR STRESS AND MASS FLOW RATE ARE CALCULATED AND PLOTTED AUTOMATICALLY
4. RECYCLE TIME ~ 1 MINUTE

Fig. 10. Construction and Operation of the Friction Tube.

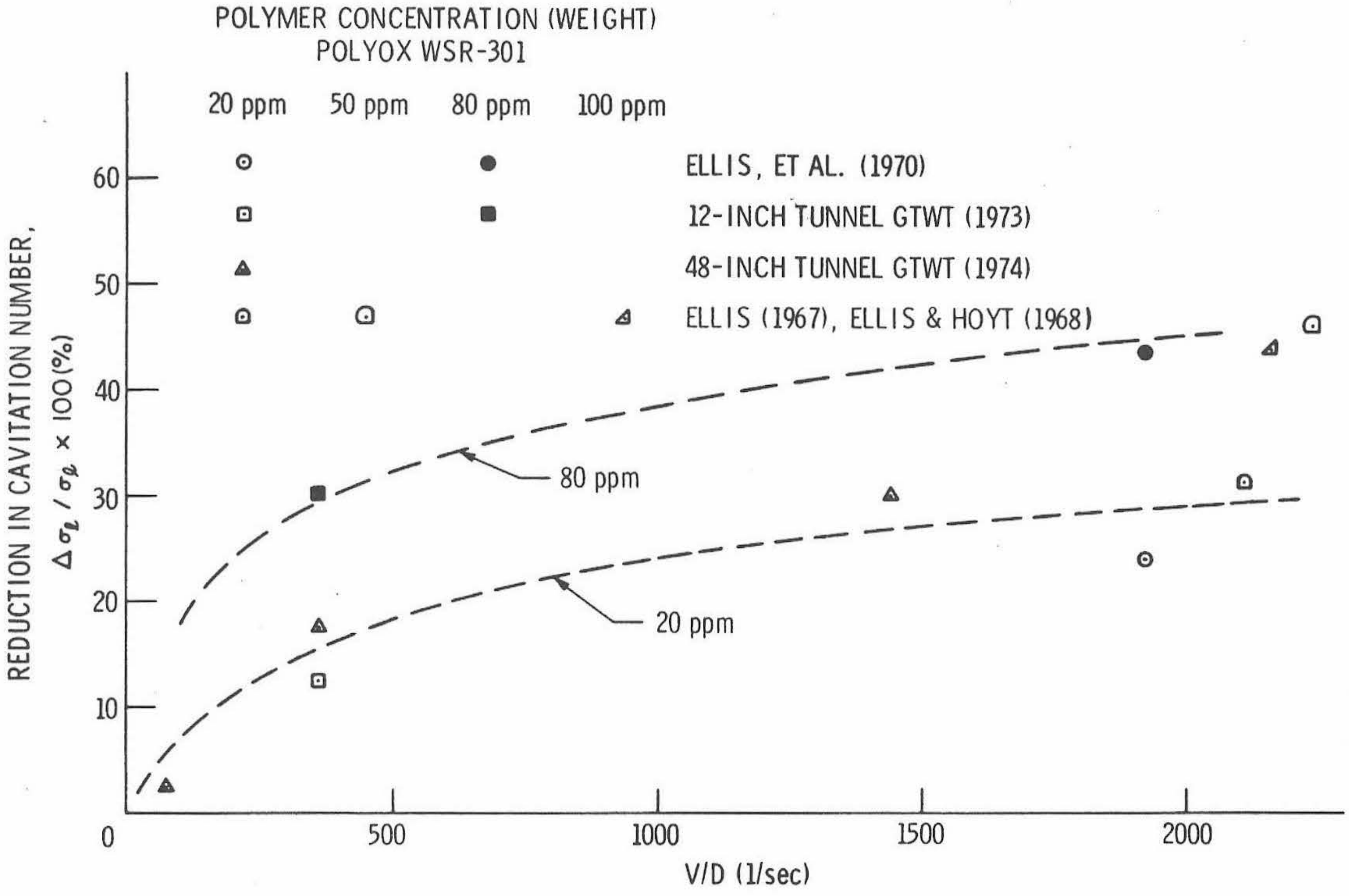


Fig. 11. Percentage Reduction in Cavitation Number Versus Velocity-to-Diameter Ratio for Hemispherical Noses in a Fresh Polymer Solution.

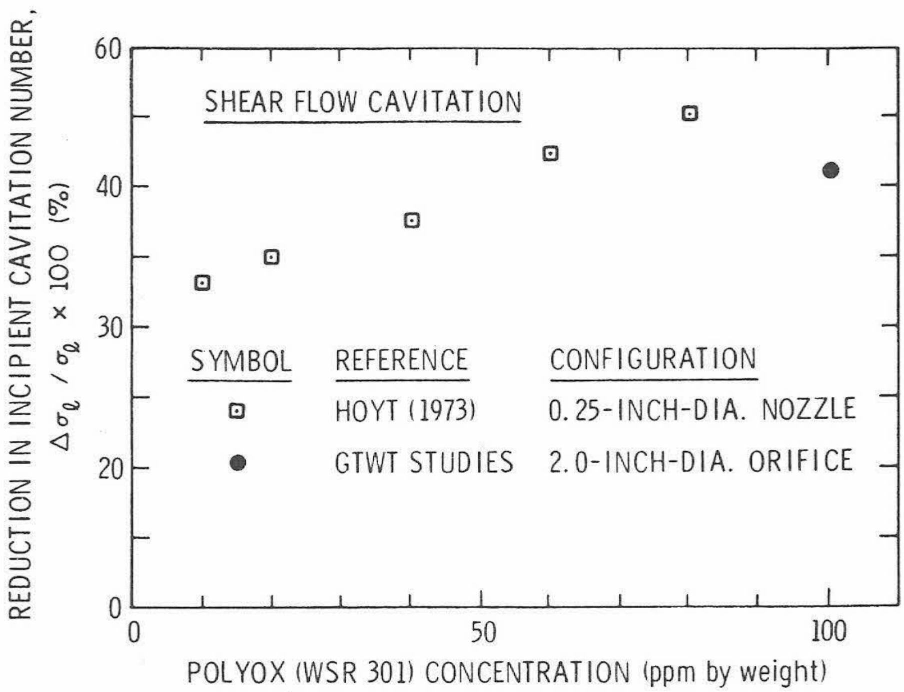


Fig. 12. Percentage Reduction in Cavitation Number Versus Polymer Concentration for Shear Flow.

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